RESTORING SURFACE WATER—GROUNDWATER CONNECTIVITY IN AN APPALACHIAN HEADWATER STREAM ON SURFACE MINED LANDS GUY COVE, KENTUCKY

Research Thesis

Submitted in partial fulfillment of the requirements for graduation

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By

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ABSTRACT

Mountaintop removal mining involves excavating coal seams and depositing the spoil in valleys, often burying headwater streams. To explore the potential for restoring these headwater streams, a reach at Guy Cove, Kentucky, was restored on top of valley fill and monitored for discharge and basic water quality parameters. The restored stream loses water to the underlying fill over much of the year and sometimes vanishes before the end of the reach. In this study, we measured infiltration rates along the streambed using heat as a natural tracer in order to characterize locations of stream loss. Measurements were taken in mid-summer and late fall at eight locations representative of riffles, runs, and pools. The stream lost water to the underlying fill at most locations during both seasons, but losses were greater during the drier fall season. Rates of infiltration or exfiltration varied strongly along this reach and showed no clear relationship with morphology. The degree of compaction and the permeability of the streambed were not measured but may control infiltration rates. If so, streambed permeability should be viewed as a critical design element in future restoration efforts.

ACKNOWLEDGEMENTS

Leading these acknowledgements is my advisor, Dr. Audrey Sawyer. Without her knowledge, guidance, and everlasting support, I would not be the student and researcher I am today. Likewise, Dr. Anne Carey proved an excellent mentor since day one, offering support on classes, extra-curricular activities, and graduate schools. Whitney Blackburn-Lynch, Tyler Sanderson, Kevin Parks, and my dad, Steve Gilmer, thank you all for being such helpful field assistants and getting down and dirty in the name of science. Bill Nye, thank you for teaching me how incredible science can be. Science rules. Bill! Bill! Bill! Bill! Bill!

To the students, staff, and faculty of The Ohio State University's School of Earth Science: your daily encouragement, push to achieve greater, and desire for my overall success has shaped me into the person and scientist I am today. Acknowledgements continue to the Friends of Orton Hall, who funded these travel and research endeavors. To those who lived through field camp, became mesmerized by Utah's national parks, and froze in the Pennsylvanian snow with me, y'all up for round two?

Finally, these acknowledgements would not be complete without the inclusion of my family. Your everlasting knowledge, love, and support has, and always will be, incredible and welcomed. I cannot thank you enough for all you have given me.

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INTRODUCTION

The act of mountaintop removal coal mining significantly alters the landscape and has become widespread in the United States. Often practiced in previously mined regions, mountaintop removal mining increases access to coal seams located on steep terrain. Each mining site must follow the 1977 Surface Mining Control and Reclamation Act, as well as other local, state, and federal laws and regulations (National Mining Association, 2009). Federal law does require excess spoil to be placed back in its original location, but the combination of increased spoil volume and steep terrain makes this process impossible at times. Thus, the spoil is placed downslope in valleys, typically covering headwater streams and meadowlands (Congressional Research Service, 2015). In the Appalachian states alone, 4.8 million hectares have been mountaintop removal mined, resulting in the burial of over 1.9 kilometers of streams (Congressional Research Service, 2015).

The burial of these streams alters natural connections between surface water and groundwater. Surface water can infiltrate into the underlying aquifer or groundwater can discharge to the stream, though a combination of both is expected along typical headwater streams (Figure 1). When headwater streams are buried by spoil, the natural movement of water changes. Ephemeral sections of stream can disappear completely, along with important wetland habitats, while stream flow may increase downstream from the fill where groundwater emerges. As groundwater flows through the added sediment, new chemicals from the fill dissolve that can significantly impair downstream water quality for terrestrial and aquatic life and humans. Also, biogeochemical conditions imperative to plant life may be directly affected (Winter et al., 1998). Water quality impacts can increase in severity as water flows down valley.

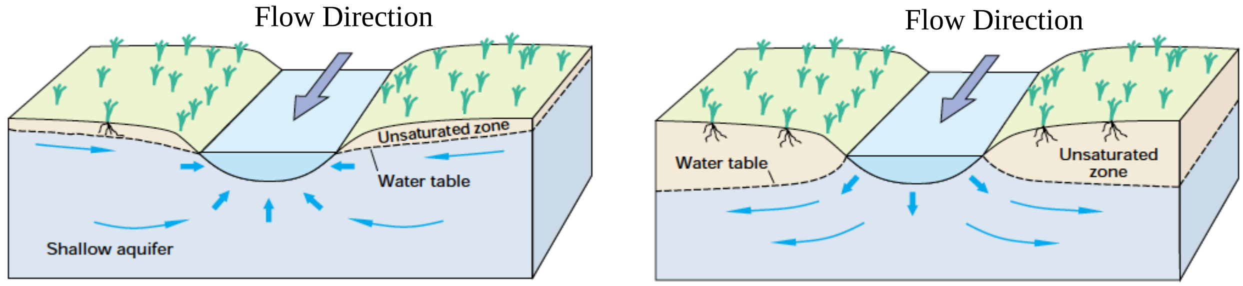


Figure 1. Streams can receive groundwater (left) or lose water to the surrounding aquifer (right) (Winter et al., 1998).

One possible approach to mitigate the effects of valley fill on stream water quality is to restore headwater streams on top of valley fill. Restoration goals could include reestablishing a healthy riparian ecosystem, restoring prior annual and storm hydrograph behavior, and minimizing excessive recharge to spoil where groundwater can interact with reactive mineral surfaces. To test the feasibility of restoring a headwater stream on valley fill, an experimental stream restoration site was established in Guy Cove, Kentucky. Here, I utilized heat as a tracer to monitor the exchange of stream water and groundwater along the restored channel. I hypothesized that stream losses would be greatest in summer when plant water use is greatest and that stream losses would diminish in the fall when plants become dormant. However, the summer monitoring period was particularly wet, while the fall monitoring period was dry, and these weather patterns had a greater influence on stream-groundwater interactions than plant activity.

SITE DESCRIPTION

In 1923, The Department of Forestry at the University of Kentucky was granted nearly 6,000 hectares of previously logged timberland. Now called Robinson Forest, this wilderness area is located in the Cumberland Plateau (Maupin, 2012) and is one of the largest research and educational forests in the eastern United States (Robinson Forest, 2015). During the 1990's, American Electric Power Kentucky Coal mined the area of Guy Cove within Robinson Forest by means of mountaintop removal (Blackburn-Lynch, 2015) (Figure 2). During this process, the University of Kentucky negotiated a restoration project with Kentucky Fish and Wildlife. Money typically allocated to diminishing the mining impact was spent on a headwater stream restoration experiment at the site led by researchers at the University of Kentucky (Agouridis, 2016).

Restoration activities on the valley fill region of Guy Cove began in 2008 (Figure 2). Restoration activities included construction of 1,400 meters of stream channel and 2,000 m^2 of vernal pools using the natural channel design approach (Harman et al., 2004). Additionally, over 30,000 trees were planted on the 16.2 hectares of stream banks in accordance with the Forestry Reclamation Approach (FRA) to minimize potential soil runoff (Blackburn-Lynch, 2015). The project was completed in 2012. For two ensuing years, the restored reach was monitored for changes in hydrology, geomorphology, water quality, vegetation, and habitat regeneration (Blackburn-Lynch, 2015). To understand flow behavior in this ephemeral reach, two weirs were installed at upstream and downstream locations (Figure 2) and were equipped with In-Situ Level TROLL® 500 (5 psig) pressure transducers. Four years of discharge records show that the annual flow duration is longer at weir 1 than weir 2. In other words, stream and groundwater contributions are insufficient to sustain flow at weir 2, particularly during dry summer and fall months from June through November (Blackburn-Lynch, 2015). The goal of the study reported herein was to understand the spatial patterns of stream loss during summer and fall along this restored intermittent stream.

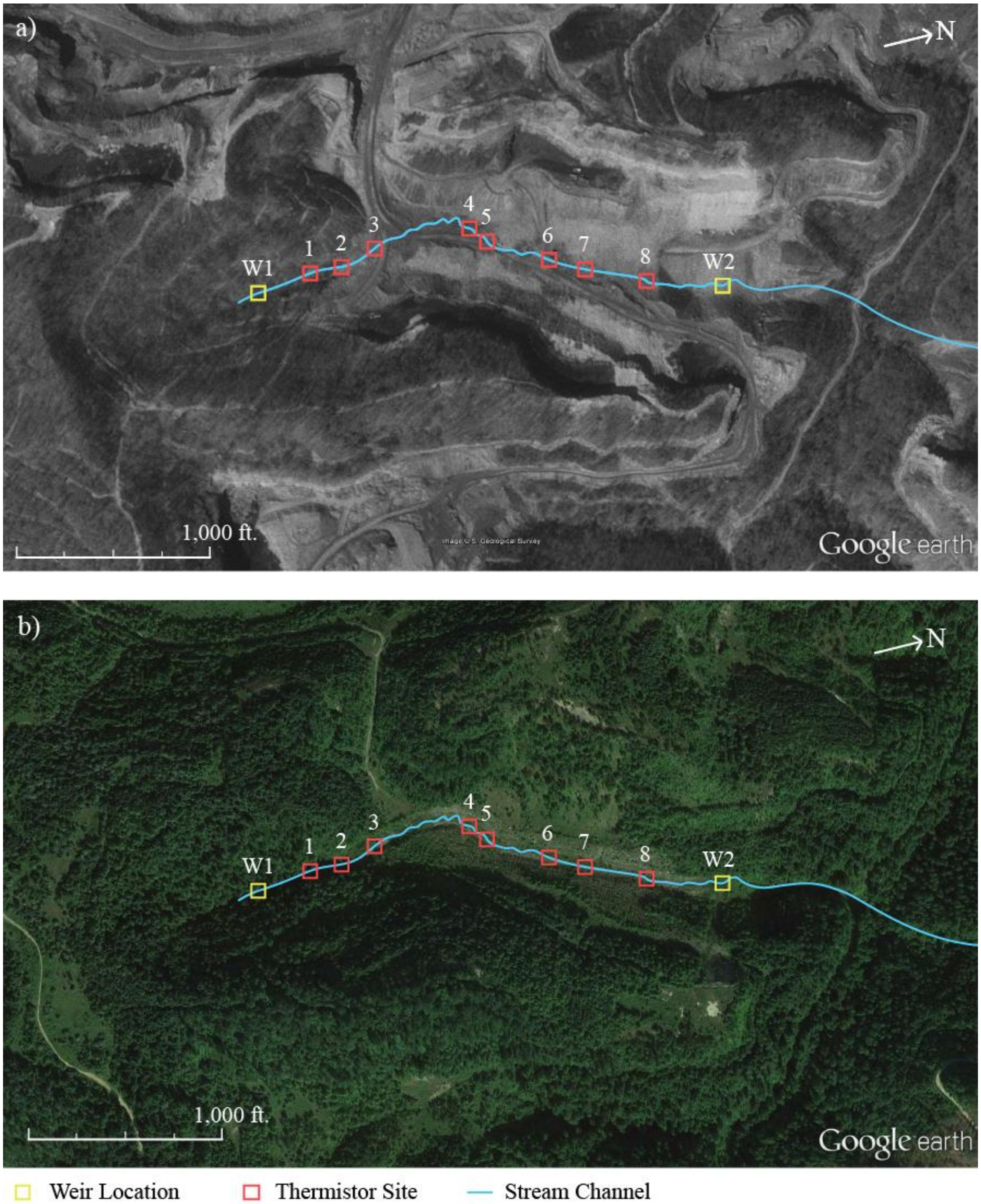


Figure 2. Satellite imagery showing Guy Cove valley during mining activities in 1995 (a) and post-restoration in 2012 (b). Flow is generally north (to the right). Weirs are shown with yellow squares, and thermistor locations are shown with red squares, numbered sequentially down flow.

METHODS

Surface water-groundwater exchange in streams has been measured with numerous approaches, including seepage meters, shallow piezometers, tracer injection, channel water balance, and heat tracing (Hatch et al., 2006). By using heat as a tracer, temperature measurements in the streambed estimate the direction and rate of vertical seepage (the Darcy velocity, q). Stream water has a relatively large daily temperature range due to direct exposure to sun and air, while groundwater has a small daily temperature range. When stream water infiltrates into the bed, it transports the stream's temperature signal downward, and amplitude of the temperature signal does not change dramatically with depth. In contrast, when groundwater with a stable temperature discharges to the stream, the amplitude decreases dramatically with depth near the streambed. These changes in the amplitude of the daily temperature signal versus depth can be used to estimate vertical Darcy velocity (Hatch et al., 2006). To determine seasonal changes in Darcy velocity at Guy Cove, temperature measurements were collected during the summer and late fall of 2015. The summer measurement week, from June 30 to July 6, was unusually wet with multiple rain events, while the fall measurement period, from November 8 to December 2, was unusually dry.

Sensor Installation and Data Collection

On June 29, 2015, eight vertical standpipes were installed within the reconstructed reach (Figure 2, Table 1). Locations were selected to include a variety of channel features such as pools, riffles, runs, and cross-veins. A cross-vein is a log installed in the channel during restoration to reduce stream bank erosion (Rosgen, 2001). At each thermistor location, a 1.25 cm galvanized steel standpipe was filled with water, and four temperature sensors (HOBO TMC20-

HD) were inserted to depths of 5, 15, 25, and 35 cm below the sediment-water interface. The thermistors were connected to one HOBO 4-Channel External Data Logger (U12). This data logger was wrapped with plastic netting to protect against damage from wildlife (Figure 3). The loggers were programmed to record temperature every 5 minutes during the two separate field seasons in summer and late fall. Thermistors had an approximate accuracy of 0.25˚C and a resolution of 0.03˚C (Sawyer et al., 2012).

Table 1. Location of 8 thermistors and description of channel morphology. Wet/Dry indicates the presence or absence of stream water in the channel at the time of sensor deployment and recovery during both seasons.

Site	Latitude	Longitude	Description	06/28/2015 Wet?	07/07/2015 Wet?	11/07/2015 Wet?	12/03/2015 Wet?
1	37˚ 24.725 N	083˚ 10.495 W	Pool	Wet	Wet	Wet	Wet
2	37˚ 24.749 N	083˚ 10.491 W	Pool/Marsh	Wet	Wet	Wet	Wet
3	37˚ 24.780 N	083˚ 10.497 W	Cross-veined run	Wet	Wet	Wet	Wet
4	37˚ 24.858 N	083˚ 10.483 W	Riffles	Wet	Wet	Dry	Wet
5	37˚ 24.868 N	083˚ 10.464 W	Run/Slight pool	Wet	Wet	Dry	Wet
6	37˚ 24.911 N	083˚ 10.425 W	Run	Dry	Wet	Dry	Wet
7	37˚ 24.937 N	083˚ 10.402 W	Cross-veined run	Dry	Wet	Dry	Wet
8	37˚ 24.981 N	083˚ 10.366 W	Run	Wet	Wet	Dry	Wet

Summer temperature measurements were collected from June 30 to July 7, 2015, while fall temperature measurements were collected from November 8 to December 2, 2015. During these time periods, discharge was measured at the upstream and downstream weirs. Because stream temperatures had a smaller daily amplitude in fall than summer, seepage rates were more difficult to determine. We selected the six days between November 24 and 29 for detailed seepage rate analysis due to their relatively large daily temperature signals.

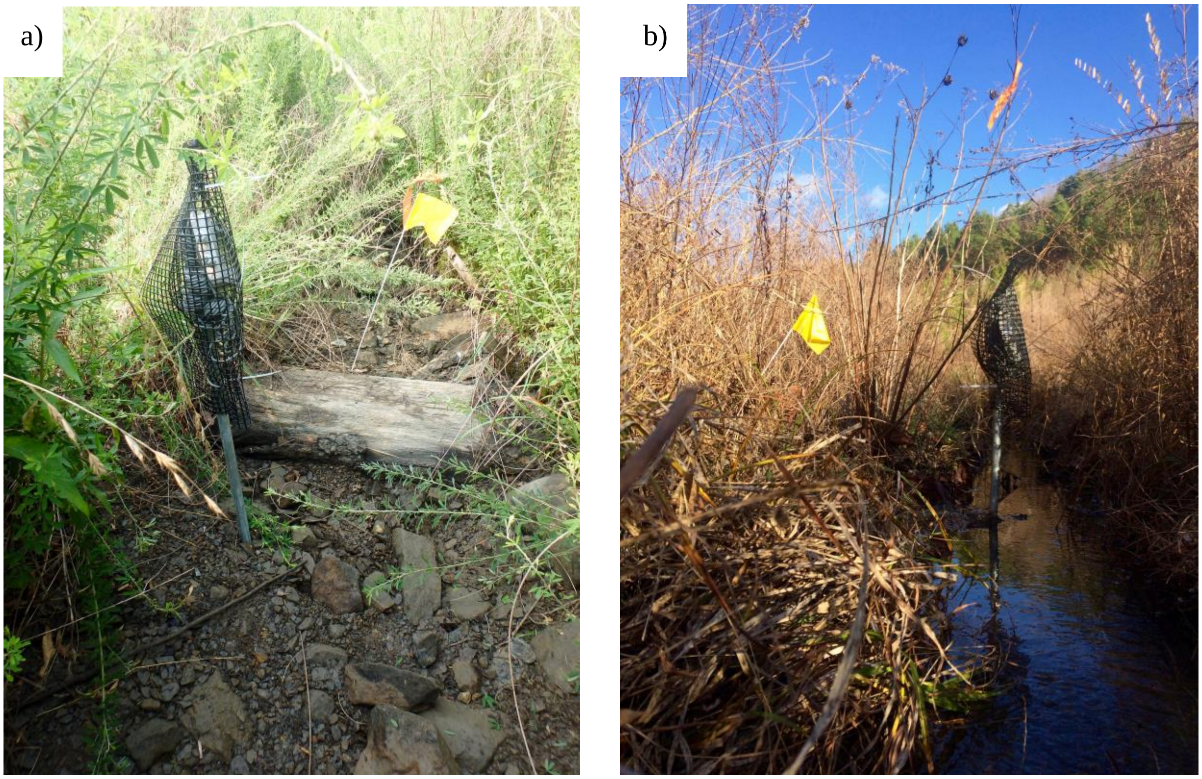


Figure 3. Photographs of thermistors during two seasons: a) Site 7 during summer when the streambed was temporarily dry and b) Site 5 upon a wet fall retrieval.

Analysis of Seepage Rates

Temperature records at each site were analyzed for Darcy velocity according to the method of Hatch et al. (2006) using the freely available code called “Ex-Stream”. The program uses a nonlinear least squares approach to estimate the amplitude of the daily temperature signal for each thermistor. Then, the program implements the Hatch et al. (2006) implicit analytical solution for the Darcy velocity based on the governing equation for heat flow in porous media:

$$\rho c \frac{\partial T}{\partial t} = -\rho_w c_w \nabla \cdot qT + \nabla \cdot \kappa \nabla T \tag{1}$$

where T is temperature, t is time, ρc is bulk specific heat (where ρ is density, and c is bulk heat capacity), q is the Darcy velocity, and κ is bulk thermal conductivity. The subscript w denotes a property of pore water. Because the thermal properties are fairly consistent across saturated sediments, the Hatch et al. (2006) solution to Equation 1 is a reasonably accurate way of constraining the Darcy velocity, which can vary by orders of magnitude. Thermal parameters for Guy Cove were calculated by assuming a porosity of 0.3 and thermal properties for water and granite (Table 2). The untested porosity estimate is within the wide range of measured values for mining spoil. Laboratory porosity tests vary up to 48%, while field tests range from 0.8% to 25% (Hawkins, 1998).

Table 2. Thermal parameters for heat tracing.

Model Parameter	**Value**	**Units**	**Symbol**
Thermal Conductivity	1.63	(J/m*s*C)	κ
Fluid Density	1,000	(kg/m^3)	ρ_w
Porosity	0.30	-	n
Specific Heat, Fluid	4,186	(J/kg*C)	$\rho_w c_w$
Specific Heat, Bulk	1,262	(J/kg*C)	ρc
Bulk Density	2,155	(kg/m^3)	ρ

The Hatch et al. (2006) method assumes one-dimensional advective-conductive transport of a daily thermal signal from the streambed into homogeneous sediment under steady fluid flow conditions. Accuracy of the estimated vertical flux is greatest when the horizontal flux component is minimal (Lautz, 2010). To gain insight into the potential accuracy of flux estimates and divergence of fluxes with depth, the Darcy velocity was analyzed at two sites for every combination of sensor pairs (Table 3). Flux estimates vary with choice of sensor depth pairs, but average flux estimates tend to be similar to estimates from the two middle sensors at 15 and 25 cm below the streambed. To analyze the remaining data for all eight sites, the two middle sensors were therefore used.

Table 3. Estimated summer seepage rates (q) at Site 3 (a) and Site 6 (b) based on different sensor depth pairs (indicated with subscripts). Analysis windows begin at 00:00 for each day. Negative vales indicate infiltration and positive values indicate exfiltration.

a)

Date	$q_{1,2}$ (cm/d)	$q_{2,3}$ (cm/d)	$q_{3,4}$ (cm/d)	$q_{1,3}$ (cm/d)	$q_{2,4}$ (cm/d)	$q_{1,4}$ (cm/d)	Average (cm/d)	St. Dev. (cm/d)
6/30/15	0.55887	1.77762	-0.14450	1.17683	0.83090	0.74237	0.82368	0.64014
7/1/15	0.85820	-1.15830	-2.28092	-0.13377	-1.71419	-0.83265	-0.87694	1.12394
7/2/15	0.69752	3.42713	7.42443	2.09040	5.48399	3.96299	3.84774	2.39468
7/3/15	-6.03311	-6.53348	-8.37993	-6.28193	-7.43613	-6.95819	-6.93713	0.86494
7/4/15	0.76460	0.98066	4.41441	0.87282	2.74170	2.09567	1.97831	1.42980
7/5/15	-3.29726	-1.42428	-1.70879	-2.34546	-1.56624	-2.13174	-2.07896	0.69088
7/6/15	0.64077	0.33599	4.00121	0.48867	2.21930	1.70138	1.56455	1.40748

b)

Date	$q_{1,2}$ (cm/d)	$q_{2,3}$ (cm/d)	$q_{3,4}$ (cm/d)	$q_{1,3}$ (cm/d)	$q_{2,4}$ (cm/d)	$q_{1,4}$ (cm/d)	Average (cm/d)	St. Dev. (cm/d)
6/30/15	-1.91978	-2.51784	-0.75290	-9.84477	-1.62221	-1.72107	-3.06309	3.37075
7/1/15	-3.13970	-3.31247	-2.27487	-8.44097	-2.78889	-2.90531	-3.81037	2.29610
7/2/15	-5.37518	-3.96572	1.12905	-6.43266	-1.30962	-2.60033	-3.09241	2.77028
7/3/15	-8.10401	-7.73858	-3.95499	-1.88565	-5.76986	-6.52041	-5.66225	2.37482
7/4/15	-4.59245	-5.14488	-7.71693	-6.12671	-6.39386	-5.77805	-5.95881	1.08356
7/5/15	-10.05869	-9.04859	-4.25763	-0.34782	-6.52275	-7.63250	-6.31133	3.55265
7/6/15	-5.69303	-5.40560	-2.46129	-5.19176	-3.89220	-4.47837	-4.52037	1.20380

RESULTS

Precipitation, Stream Flow, and Temperature

Precipitation varied greatly between seasons. Significant rain fell near the middle and at the end of the summer sampling week, reaching a maximum hourly value of 0.51 cm on July 5 at 16:00 (Figure 4a). The fall season was unusually dry and no precipitation was measured during the week analyzed (Figure 4b). During the longer deployment interval however, 0.9 cm of precipitation fell on November 18, approximately 6 days before starting of analysis (not shown).

Stream flow at the upstream and downstream weirs reflects rainfall patterns. In the summer, stream flow increased over the measurement week in response to frequent rain events, and there was a net gain of flow between weirs (Figure 5a). Upon summer deployment, dry areas of streambed were observed at locations 6 and 7, but the channel was wet again at location 8 (Table 1). These local observations suggest that most of the gains between weirs were focused in the lower portion of the reach downstream from location 7. During the fall, stream flow was steady over the measurement week, and there was a net loss of flow between weirs (Figure 5b). Upon fall deployment, all locations downstream from site 3 were dry at the start of the temperature measurements (Figure 2), but there was measurable flow at the lower weir. It is important to note that net gains or losses between the weirs are not necessarily representative of average stream-aquifer interactions along the reach but may depend heavily on areas of focused groundwater discharge just upstream from the lower weir.

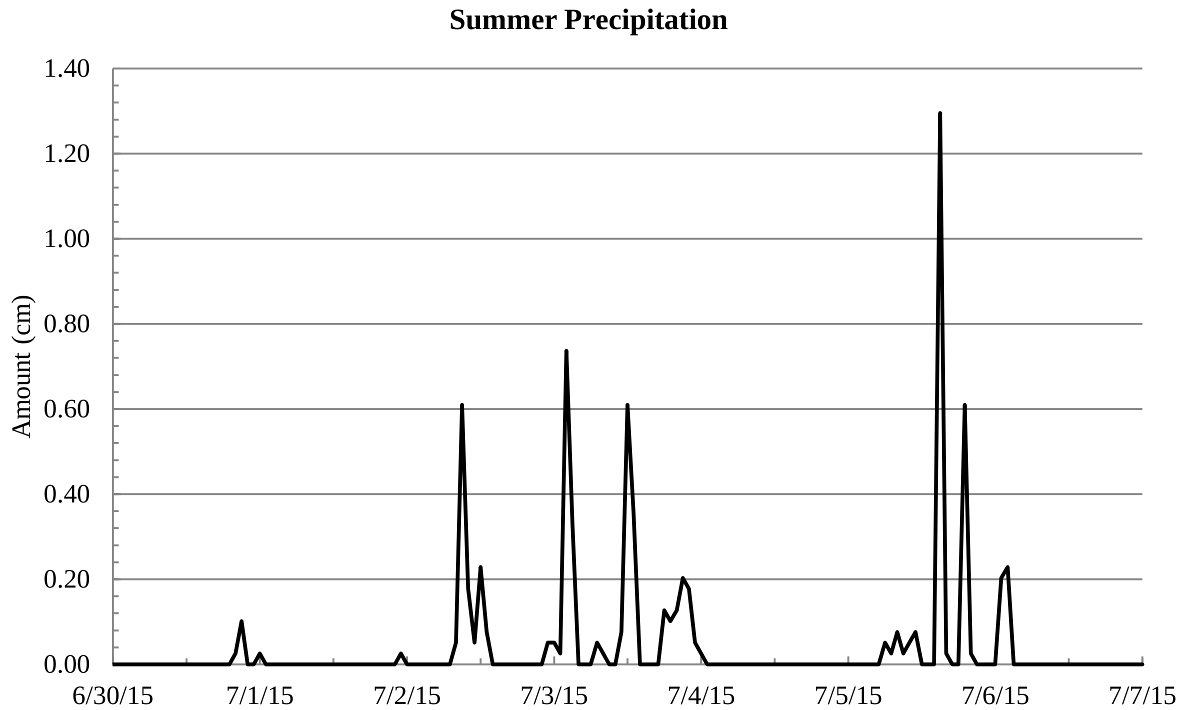
Temperature fluctuations at the shallowest streambed thermistors generally ranged over 2 and 4 degrees Celsius during the summer, but only 1 to 2 degrees during the fall (Figure 6). Temperatures deeper in the soils have even smaller daily ranges. Temperature data could not be analyzed at some sites due to disruptions or damage. For example, temperature anomalies were recorded at Site 4 beginning on July 2 (Figure 6c) and the sensors at that site were found lying in the stream next to the standpipe upon summer instrument retrieval. Bite marks on cables and matted vegetation suggest damage by wildlife (presumably elk) rather than humans.

Seepage Rates

Water exchange across the streambed was negative (indicating infiltration) over most sites and measurements dates, suggesting frequent and pervasive losses of stream water to the underlying valley fill (Figures 8–11). The mean seepage rate for both measurement seasons was -7.6 cm/d (n=172). Infiltration rates were greater during the dry fall season than the wet summer season. The mean summer flux was -4.4 cm/d (n=52). The mean fall flux was -4.8 cm/d (n=24). An analysis of the entire fall dataset suggests average fall infiltration rates were even greater (-8.9 cm/d, n=120, Appendix 1). Short periods of higher infiltration occurred in association with precipitation events, while prolonged dry periods tended to produce more stable infiltration rates. The greatest summer infiltration rate was associated with a rain event on July 5 at Site 7 (-38.2 cm/d, Figure 8a). The greatest fall infiltration rate was -62.3 cm/d at Site 5 on November 20 (Appendix 1). The maximum summer exfiltration rate was 11.2 cm/d at Site 2 on July 4, while the maximum fall exfiltration rate was 21 cm/d at Site 7 on November 19 (Appendix 1).

Spatial patterns of seepage were relatively consistent across seasons, and the predominant direction of flow was downward from the channel into the fill (Figures 9 and 10). Site 1 was located in the first pool downstream from the upper weir and exhibited relatively stable infiltration across both seasons. Site 2 was located in an area where the channel widens into a marsh. This location was wet during all installations and retrieval dates, and it was the only location with strong exfiltration (Figures 9 and 10). Site 3, located in a run with cross-veins, was relatively neutral and alternated between infiltration and exfiltration over precipitation events (Figures 8a and 9). Site 4, located in a riffle, could only be analyzed over 8 days due to disturbance during the summer and fall but exhibited consistently strong infiltration. Site 5 (another run) was similar in behavior to Site 3 where seepage rates varied with periods of precipitation. Seepage rates at Site 5 displayed infiltration during both seasons, but greater values were measured in the drier fall season (Figure 8).

Sites 6, 7, and 8 were located in runs with a notable increase in channel grade. Site 6 had consistent but low rates of infiltration across summer (Figure 8a). The fall period could not be analyzed. Unlike Site 6, seepage rates at Site 7 were variable. Infiltration consistently spiked due to summer precipitation events and infiltration rates remained high after the second event on July 2 (Figure 8a). Seepage rates were also variable in the fall measurement period (Appendix 1). At Site 8, flowing water was present in summer when Sites 6 and 7 were dry. A spring may exist between Sites 7 and 8. In both summer and fall, Site 8 tended to exhibit infiltration.



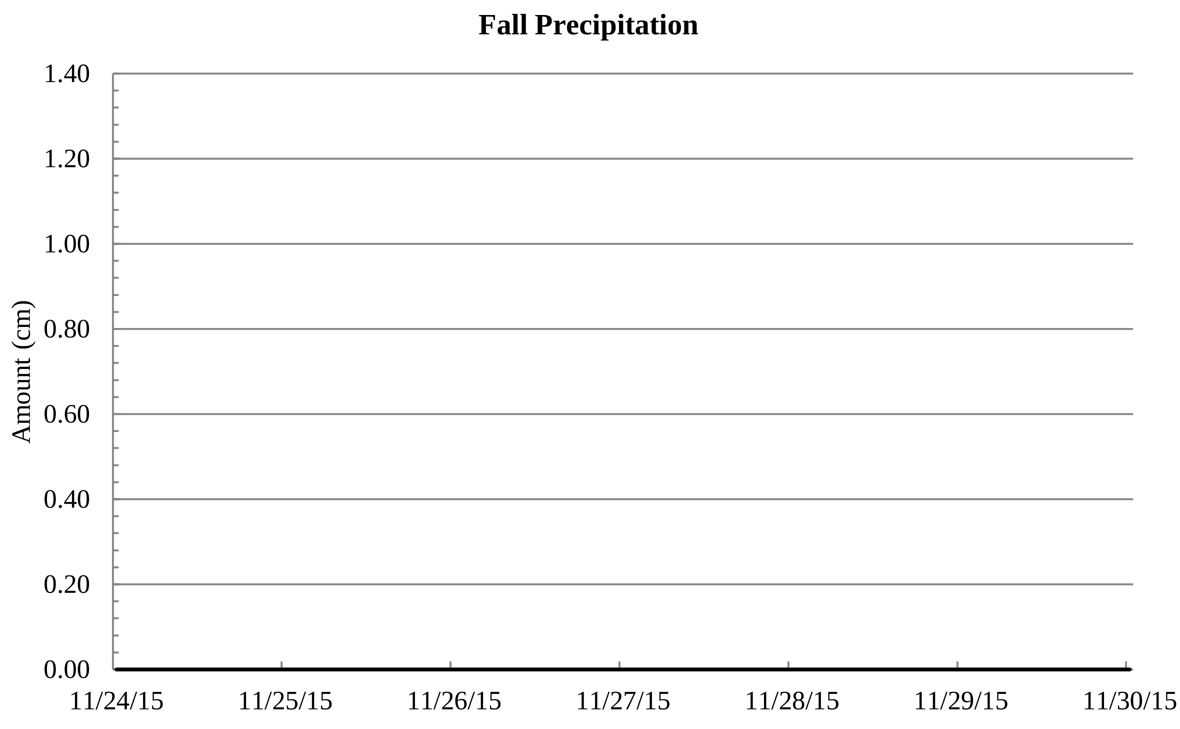
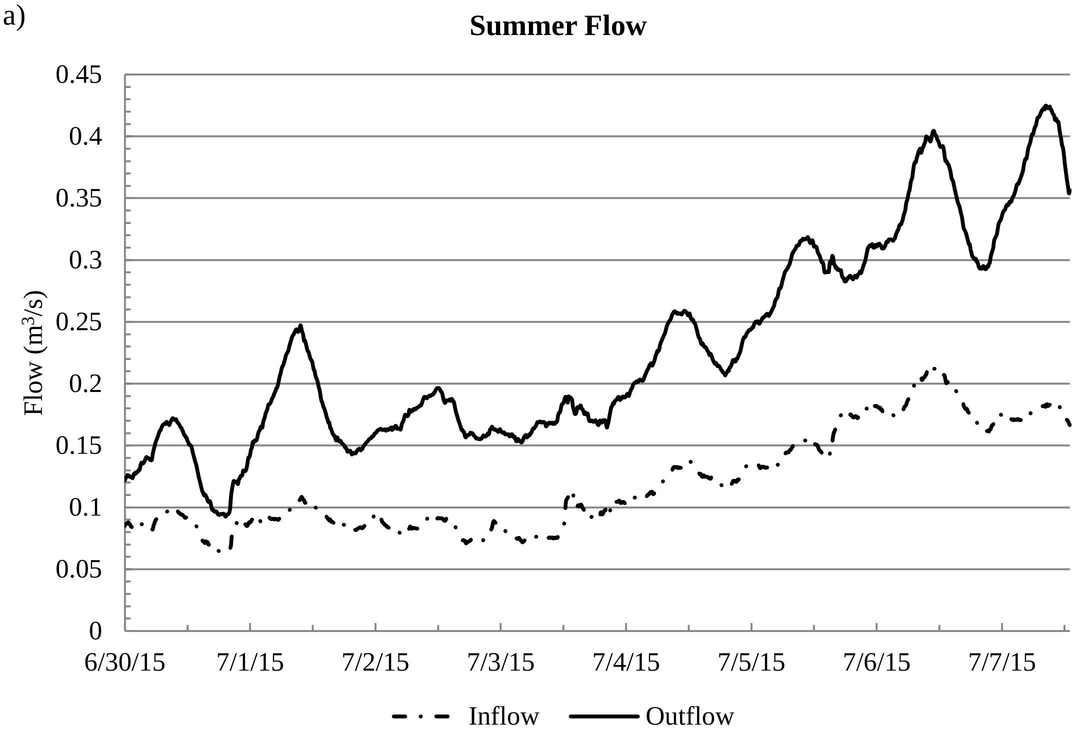


Figure 4. Precipitation measured at an observation station in Robinson Forest.

a)



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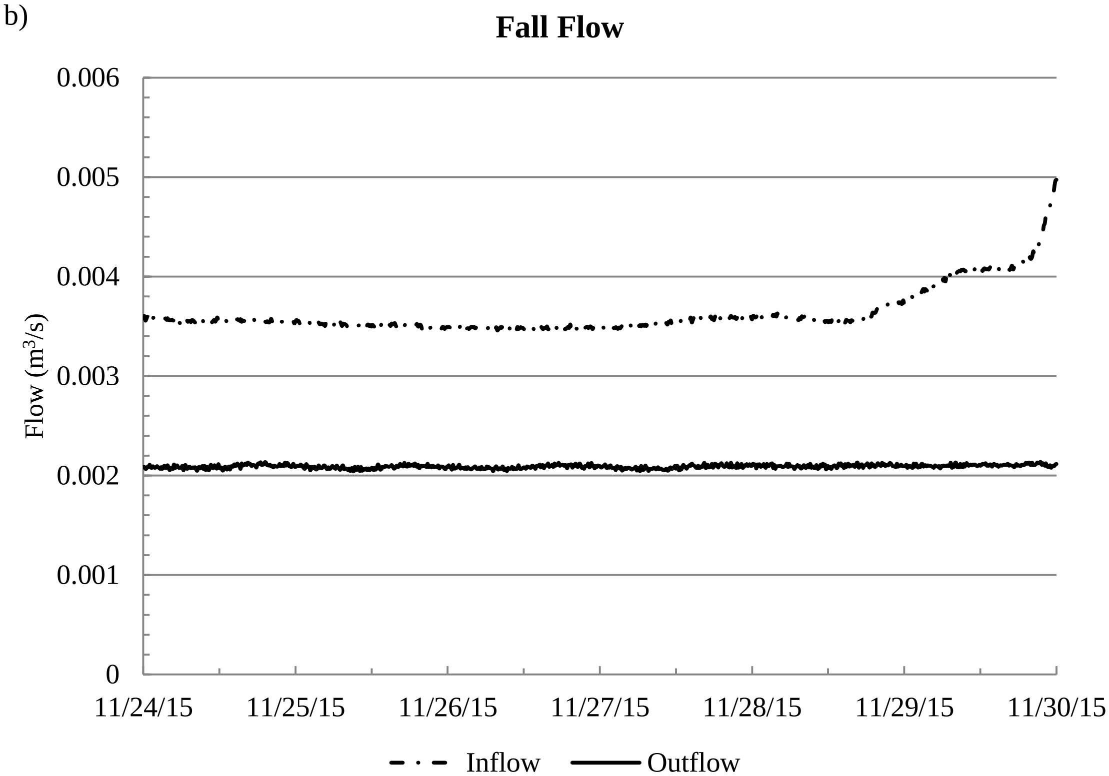


Figure 5. Stream flow at upstream and downstream weirs (locations are shown in Figure 2).

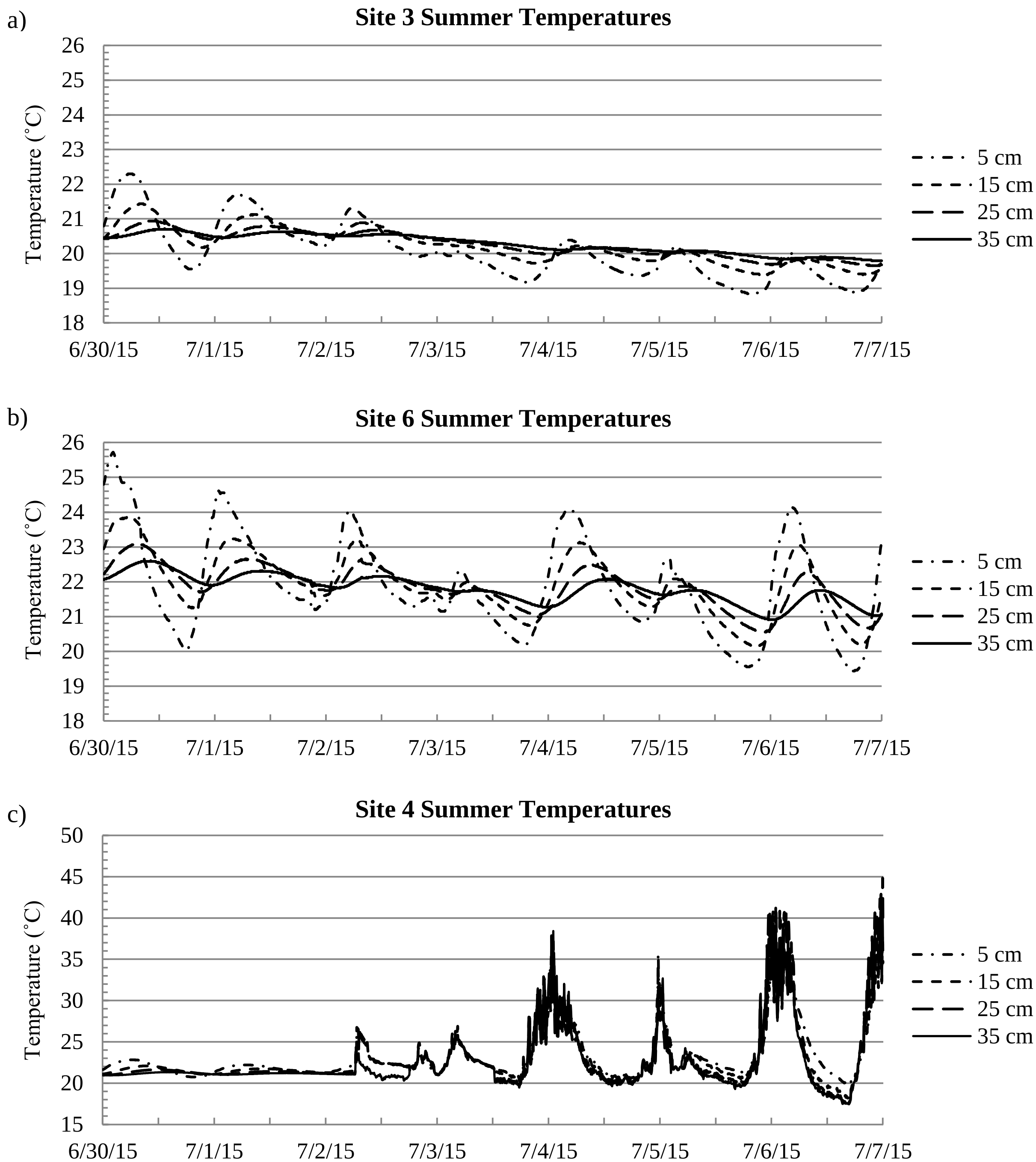
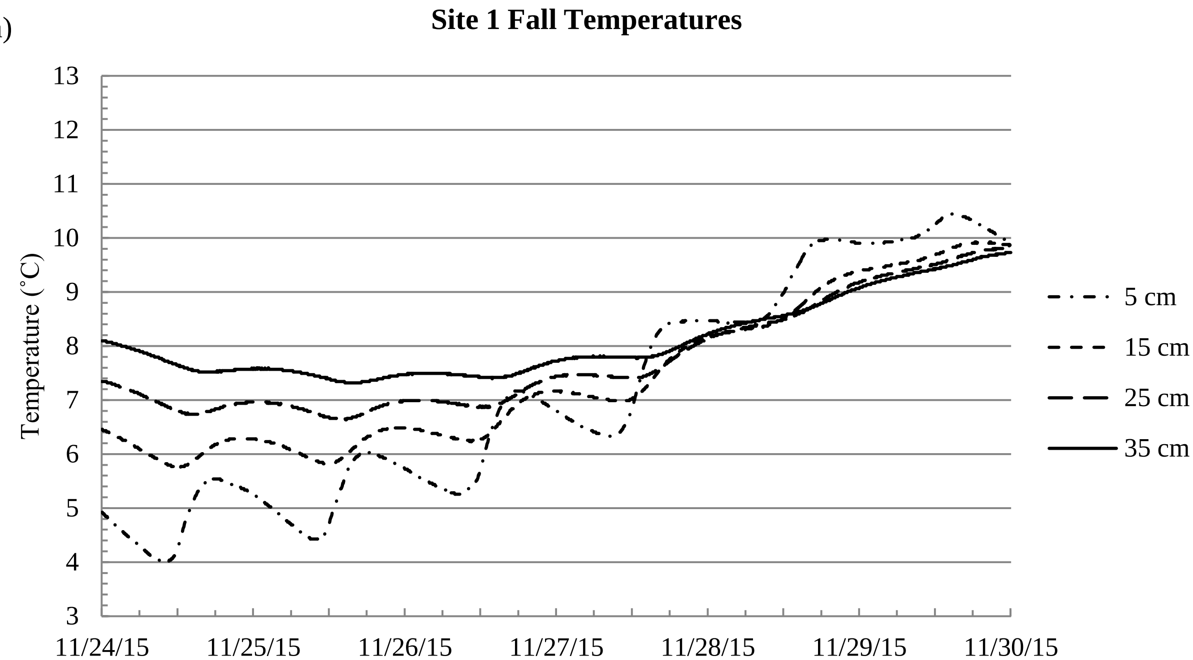


Figure 6. Streambed temperature measurements at Site 3 (a), Site 6 (b), and Site 4 (c). Sites 3 and 6 displayed normal daily temperature fluctuations. Site 4 is an example of a location where wildlife disturbed sensors (note anomalies beginning on July 2, 2015).

a)



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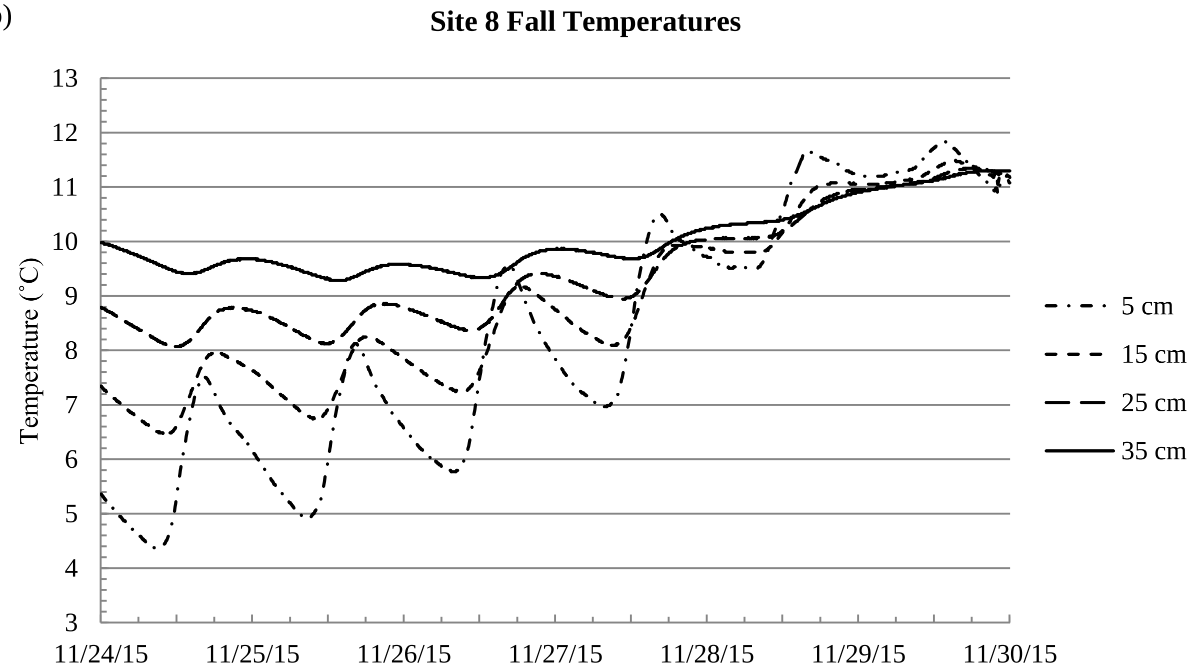
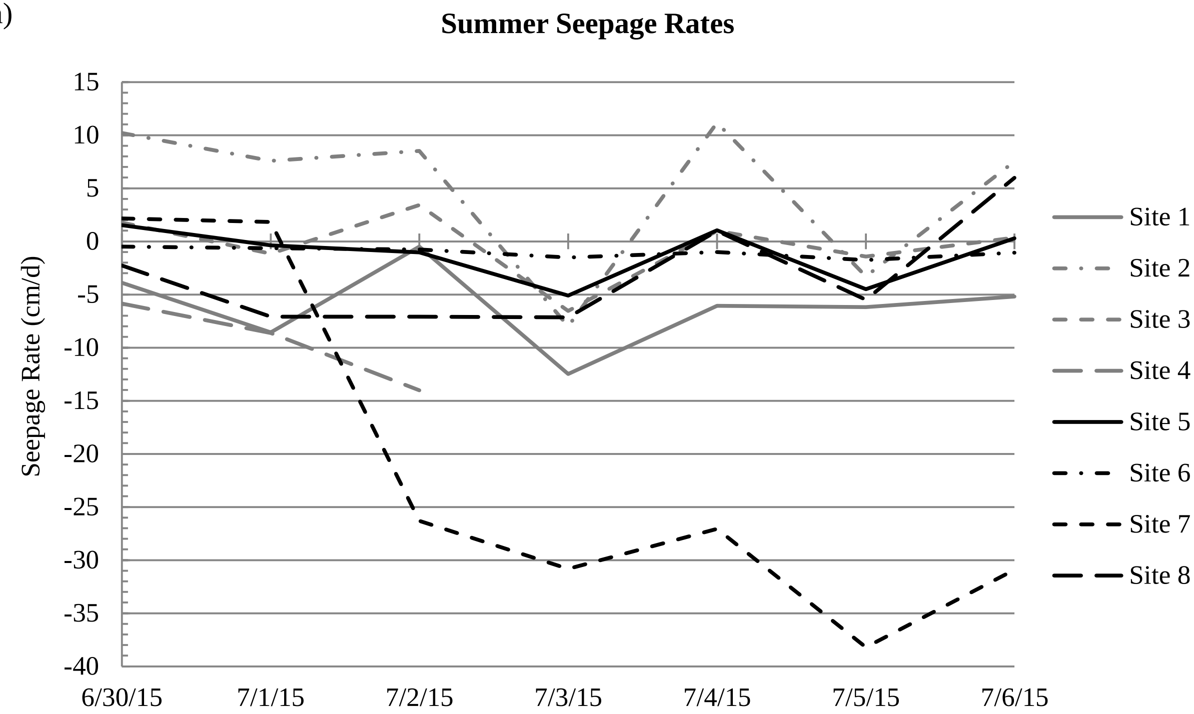


Figure 7. Streambed temperatures at Site 1 (a) and Site 8 (b).

a)



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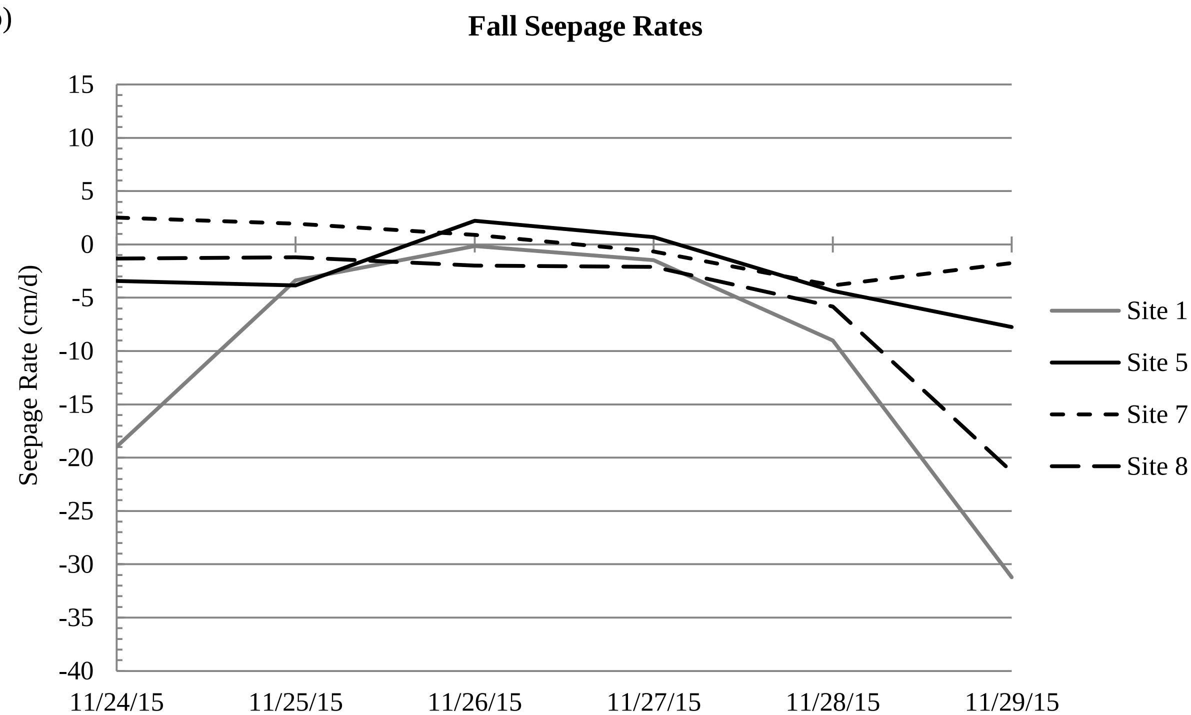

Figure 8. Daily seepage rates at each site along the reach during summer (a) and fall (b) periods. Negative values indicate infiltration and positive values indicate exfiltration.

Table 4. Seepage rates in summer (a) and fall (b) measurement periods. Infiltration is represented with negative values; exfiltration is represented with positive values. See Appendix 1 for seepage rates over entire fall dataset.

a)

Date	Site 1 *q* (cm/d)	Site 2 *q* (cm/d)	Site 3 *q* (cm/d)	Site 4 *q* (cm/d)	Site 5 *q* (cm/d)	Site 6 *q* (cm/d)	Site 7 *q* (cm/d)	Site 8 *q* (cm/d)
6/30/15	-3.88793	10.20135	1.77768	-5.85010	1.53383	-0.49098	2.15350	-2.27250
7/01/15	-8.56315	7.57186	-1.15820	-8.61114	-0.38671	-0.64593	1.82256	-7.07630
7/02/15	-0.50332	8.50192	3.42703	-14.02227	-1.02779	-0.77331	-26.30532	-7.07630
7/03/15	-12.49011	-7.98836	-6.53342	*	-5.08774	-1.50902	-30.83683	-7.14614
7/04/15	-6.06435	11.17856	0.98066	*	1.05342	-1.00325	-27.07540	0.99594
7/05/15	-6.18212	-3.30341	-1.42427	*	-4.50244	-1.76447	-38.20935	-5.48066
7/06/15	-5.20294	7.51034	0.33601	*	0.27605	-1.05409	-30.92191	5.97148

b)

Date	Site 1 *q* (cm/d)	Site 2 *q* (cm/d)	Site 3 *q* (cm/d)	Site 4 *q* (cm/d)	Site 5 *q* (cm/d)	Site 6 *q* (cm/d)	Site 7 *q* (cm/d)	Site 8 *q* (cm/d)
11/24/15	-18.9758	*	*	*	-3.4105	*	2.5029	-1.3257
11/25/15	-3.3621	*	*	*	-3.8308	*	1.9518	-1.2163
11/26/15	-0.1665	*	*	*	2.2265	*	0.8931	-1.9992
11/27/15	-1.4623	*	*	*	0.6734	*	-0.6662	-2.1117
11/28/15	-9.0230	*	*	*	-4.3424	*	-3.8511	-5.8260
11/29/15	-31.2169	*	*	*	-7.7601	*	-1.7534	-21.3157

* denotes disturbance and/or damage by elk
** denotes poor temperature time series fit, analysis was conducted with depths 3 and 4.
***denotes poor temperature time series fit, analysis was conducted with depths 1 and 2.

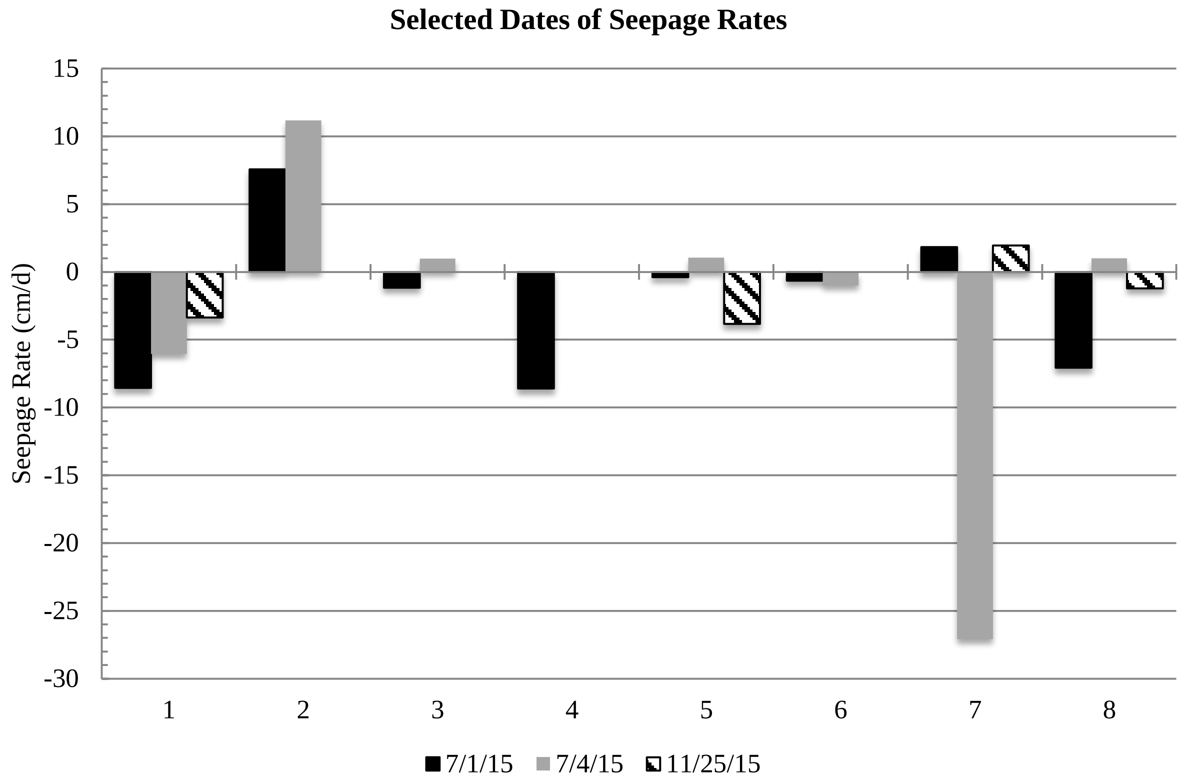

Figure 9. Spatial patterns in seepage rate on select dates.

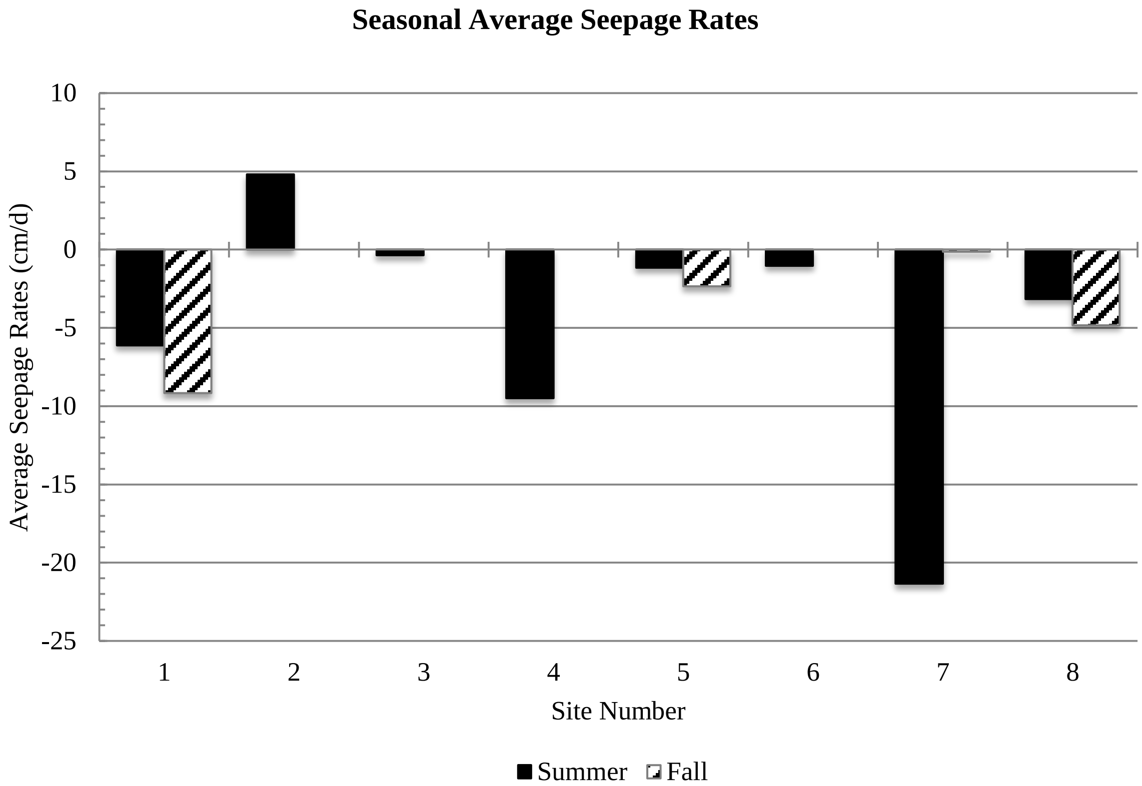

Figure 10. Patterns in average summer and fall seepage rates along the reach. Sites 2, 3, 4, and 6 are missing fall data due to disruptions to sensors. Negative values indicate infiltration and positive values indicate exfiltration.

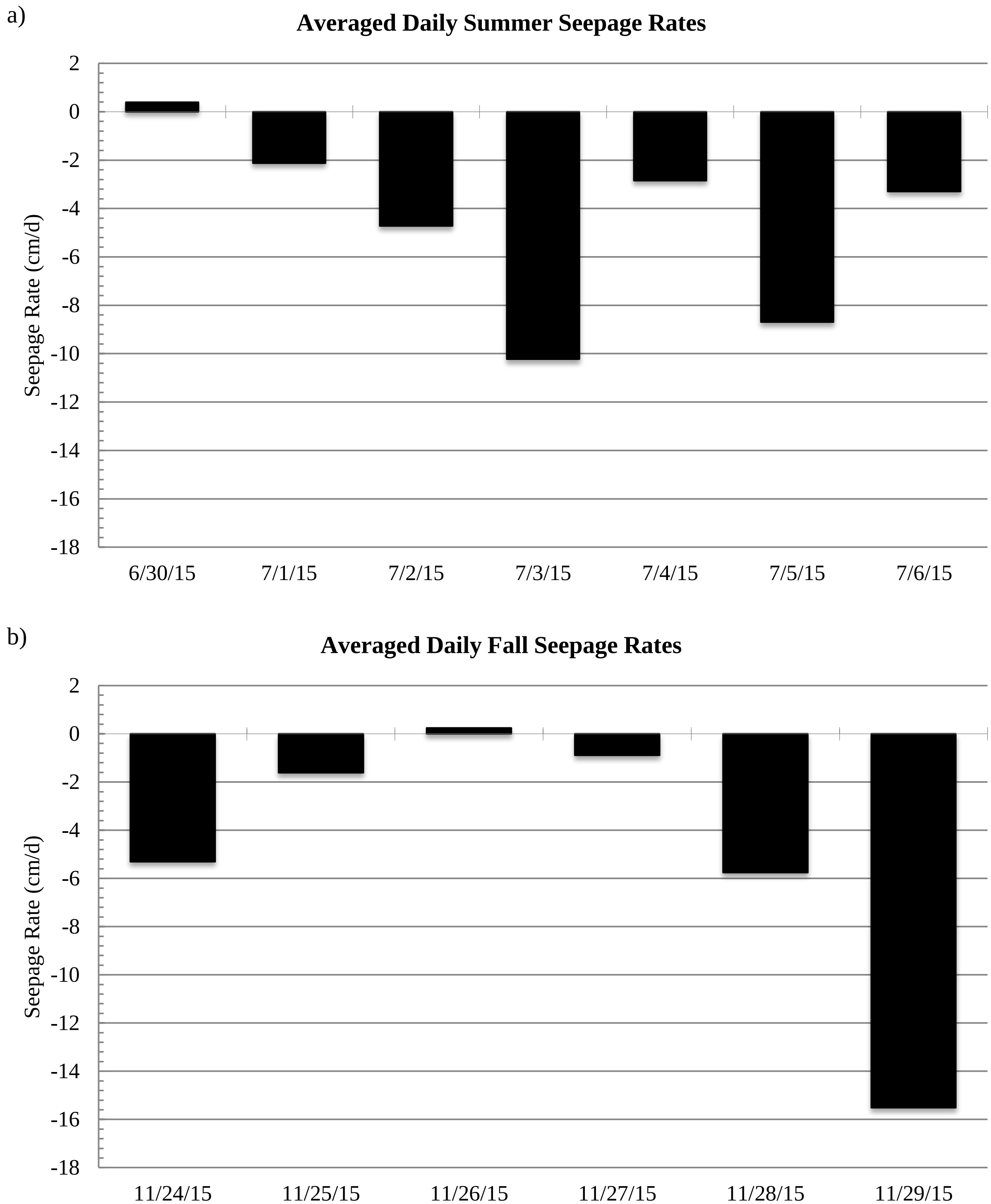

Figure 11. Average seepage rates across the reach on each day of summer (a) and fall (b) deployment.

DISCUSSION

Typically, measured infiltration rates were greater in the dry fall season than the wet summer season. These results are roughly consistent with stream flow measured at the weirs. Specifically, weir records show net gains in the summer and losses in the fall (Figure 5). The apparent gain in flow during the summer (despite a tendency towards infiltration at thermistor locations) may be due to discharge at a spring downstream from Sites 8. In this case, weir measurements are not entirely representative of local seepage rates between Sites 1 and 8.

This analysis shows that weather has a large effect on local infiltration and exfiltration in the restored reach. The original hypothesis was that plant water use would control seasonal stream-aquifer interactions and that infiltration would dominate in the summer. However, extremely dry fall weather created conditions that favored more infiltration in the fall, even after plants had senesced and were using little water. Periods of exfiltration occurred in both seasons but were generally short-lived in both, and site-averaged seepage rates were only positive for one day in either summer or fall (Figure 11). At individual sites, peak infiltration rates often occurred on rainy days and were directly followed by more rapid exfiltration. During rain events, it is interpreted that stream discharge increased, and a portion infiltrated into the fill. Recently infiltrated groundwater then returned to the channel later at local discharge points (Figure 8).

Overall, spatial patterns in infiltration and exfiltration are present along the restored reach across seasons (Figure 10) but these patterns appear unrelated to stream morphology. Pools, riffles, and runs showed no tendency towards infiltration or exfiltration. Also, the visible change in channel grade after Site 5 had no effect on measured infiltration (Figure 10). Site 7 had the largest infiltration rate for any season and thermistor location but had no distinguishing features.

Furthermore, possible springs downstream from Site 7 may have caused water to reappear at Site 8 in summer and at the lower weir in both seasons. It is possible spatial patterns in infiltration and exfiltration are due to some other unobserved channel characteristics such as permeability and compaction of the bed materials.

CONCLUSIONS

Seepage rates along a restored headwater stream in Guy Cove, Kentucky, varied strongly with weather over both rain events and seasons. In general, infiltration rates were greater during the dry fall season than the wet summer season, even though plant water use would have been lower in fall. Spatial patterns in stream gains and losses were relatively consistent across seasons but appeared unrelated to channel morphology. Instead, these patterns may be associated with streambed permeability and compaction. The effects of stream restoration on permeability and stream-aquifer interactions are therefore an important area for future research.

RECOMMENDATIONS FOR FUTURE WORK

Future analyses of this site should seek to resolve some of the ambiguities behind seepage rate patterns by researching the rock types and fill properties that were placed along the reach. For example, knowledge of whether the fill had been pulverized or left in large boulders would allow for a greater understanding of the research site. Geophysical surveys and soil pits should be used to assess fill characteristics and test for relationships with infiltration along the restored reach. As noted earlier, porosities in fill vary from 0.8% to 48% between laboratory and field experiments and permeability likely varies by orders of magnitude. While an average porosity of 30% was assumed in this study, it should be measured locally with direct samples and geophysical techniques.

Conduct of research in rural Kentucky provided beautiful views during installation and retrieval of the thermistors, but the site was relatively difficult to access from The Ohio State University. The ability to do frequent instrument checks would have increased data quality, specifically for the fall measurement period. Similarly, a better defense system against the area's elk population may have prevented data loss and instrument damage.

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APPENDIX

Appendix Table 1. Seepage rates for entire fall dataset. Infiltration is represented with negative values; exfiltration is represented with positive values.

Date	Site 1 *q* (cm/d)	Site 2 *q* (cm/d)	Site 3 *q* (cm/d)	Site 4 *q* (cm/d)	Site 5 *q* (cm/d)	Site 6 *q* (cm/d)	Site 7 *q* (cm/d)	Site 8 *q* (cm/d)
11/08/15	-27.0555	-12.8468	-17.1490	-12.5151	-14.9866	-47.0453	-26.0055	-20.5592
11/09/15	-11.9371	-32.2048	-12.8166	-9.1424	3.9131	*	5.8144	0.4382
11/10/15	-14.6353	0.8752	-0.1812	-6.4263	8.7842	*	10.3631	6.4377
11/11/15	-28.4579	-34.3010	-19.3124	-7.8379	-7.4328	*	0.6209	-4.0230
11/12/15	-5.9875	7.8393	1.0165	-10.8420	-2.2031	*	-1.9594	-6.8511
11/13/15	-19.5785	-7.5553	-10.2932	*	-27.8714	*	-15.3195	-13.7091
11/14/15	-20.2050	-20.5999	-28.9534	*	-26.7752	*	*8.8398*	-29.0465
11/15/15	-29.1422	*	*	*	-2.0848	*	-12.8187	-1.1769
11/16/15	-4.7541	*	*	*	4.3197	*	1.6719	-0.6643
11/17/15	-6.9773	*	*	*	-2.4636	*	-2.8177	-4.3562
11/18/15	-4.9690	*	*	*	-4.0181	*	-6.4886	-6.1188
11/19/15	-8.4943	*	*	*	-0.7876	*	21.0269	-13.3149
11/20/15	-17.4922	*	*	*	-62.2678	*	8.8750	-13.5005
11/21/15	-19.6147	*	*	*	-1.6569	*	3.8471	-1.4852
11/22/15	-19.2685	*	*	*	-22.5894	*	16.9410	-13.8985
11/23/15	-18.0663	*	*	*	-19.0369	*	12.9697	-33.1675
11/24/15	-18.9758	*	*	*	-3.4105	*	2.5029	-1.3257
11/25/15	-3.3621	*	*	*	-3.8308	*	1.9518	-1.2163
11/26/15	-0.1665	*	*	*	2.2265	*	0.8931	-1.9992
11/27/15	-1.4623	*	*	*	0.6734	*	-0.6662	-2.1117
11/28/15	-9.0230	*	*	*	-4.3424	*	-3.8511	-5.8260
11/29/15	-31.2169	*	*	*	-7.7601	*	-1.7534	-21.3157
11/30/15	-4.3103	*	*	*	-3.0821	*	-27.7702	-9.8398
12/01/15	-17.8384	*	*	*	-12.6555	*	-25.8510	-16.4497
12/02/15	*3.1343*	*	*	*	11.5554	*	-13.9500	*14.4560*

* denotes removal from standpipe and/or damage by elk

Underlined values denote poor temperature time series fit, analysis was conducted with depths 3 and 4.

Italicized values denote poor temperature time series fit, analysis was conducted with depths 1 and 2.